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# Mapping water in protostellar outflows with *Herschel*<sup>★</sup>

## PACS and HIFI observations of L1448-C<sup>★★</sup>

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### ABSTRACT

**Context.** Water is a key probe of shocks and outflows from young stars because it is extremely sensitive to both the physical conditions associated with the interaction of supersonic outflows with the ambient medium and the chemical processes at play.

**Aims.** Our goal is to investigate the spatial and velocity distribution of H<sub>2</sub>O along outflows, its relationship with other tracers, and its abundance variations. In particular, this study focuses on the outflow driven by the low-mass protostar L1448-C, which previous observations have shown to be one of the brightest H<sub>2</sub>O emitters among the class 0 outflows.

**Methods.** To this end, maps of the o-H<sub>2</sub>O 1<sub>10</sub>–1<sub>01</sub> and 2<sub>12</sub>–1<sub>01</sub> transitions taken with the *Herschel*-HIFI and PACS instruments, respectively, are presented. For comparison, complementary maps of the CO(3–2) and SiO(8–7) transitions, obtained at the JCMT, and the H<sub>2</sub> S(0) and S(1) transitions, taken from the literature, were used as well. Physical conditions and H<sub>2</sub>O column densities were inferred using large velocity gradient radiative transfer calculations.

**Results.** The water distribution appears to be clumpy, with individual peaks corresponding to shock spots along the outflow. The bulk of the 557 GHz line is confined to radial velocities in the range  $\pm 10$ –50 km s<sup>–1</sup>, but extended emission at extreme velocities (up to  $v_r \sim 80$  km s<sup>–1</sup>) is detected and is associated with the L1448-C extreme high-velocity (EHV) jet. The H<sub>2</sub>O 1<sub>10</sub>–1<sub>01</sub>/CO(3–2) ratio shows strong variations as a function of velocity that likely reflect different and changing physical conditions in the gas that is responsible for the emissions from the two species. In the EHV jet, a low H<sub>2</sub>O/SiO abundance ratio is inferred, which could indicate molecular formation from dust-free gas directly ejected from the proto-stellar wind. The ratio between the two observed H<sub>2</sub>O lines and the comparison with H<sub>2</sub> indicate *averaged*  $T_{\text{kin}}$  and  $n(\text{H}_2)$  values of  $\sim 300$ –500 K and  $5 \times 10^6$  cm<sup>–3</sup>, respectively, while a water abundance with respect to H<sub>2</sub> of about  $0.5$ – $1 \times 10^{-6}$  along the outflow is estimated, in agreement with results found by previous studies. The fairly constant conditions found all along the outflow imply that evolutionary effects on the timescales of outflow propagation do not play a major role in the H<sub>2</sub>O chemistry.

**Conclusions.** The results of our analysis show that the bulk of the observed H<sub>2</sub>O lines comes from post-shocked regions where the gas, after being heated to high temperatures, has already been cooled down to a few hundred K. The relatively low derived abundances, however, call for some mechanism that diminishes the H<sub>2</sub>O gas in the post-shock region. Among the possible scenarios, we favor H<sub>2</sub>O photodissociation, which requires the superposition of a low-velocity nondissociative shock with a fast dissociative shock able to produce a far-ultraviolet field of sufficient strength.

**Key words.** stars: formation – stars: winds, outflows – ISM: abundances – ISM: molecules – ISM: jets and outflows – ISM: individual objects: L1448

## 1. Introduction

The earliest stages of star formation are characterized by strong mass loss, which is at the origin of observationally prominent phenomena, such as shocks and molecular outflows. The high

velocity of the shocked gas and the elevated gas temperature strongly modify the chemical composition of the gas. Depending upon the initial conditions, processes that alter the gas composition include gas dissociation and ionization, high-temperature chemical reactions and dust grain reprocessing (e.g. Flower et al. 2010). These processes produce observable signatures in the form of emission from specific molecular and/or atomic lines, the study of which is crucial not only as a probe of the shock chemistry, but also for understanding the complex interaction between wind/jet-shocks and large-scale outflows.

<sup>★</sup> *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

<sup>★★</sup> Appendices are available in electronic form at <http://www.aanda.org>

Among the different tracers, lines of  $\text{H}_2$  and CO are routinely used to infer the physical conditions and the dynamics of shocked gas, while less abundant molecules, such as SiO or  $\text{CH}_3\text{OH}$  are sensitive to the chemical processes triggered in the shocked gas. In this framework, water can be considered a key molecule: in fact, the  $\text{H}_2\text{O}$  relative line intensities and its column density are subject to strong variations that are highly dependent on the actual physical conditions of the gas but also on its thermal and chemical history. This is because the water abundance strongly depends on the mechanism of evaporation/freeze-out in grain mantles and the endothermic gas-phase chemical reactions that drive all free oxygen into water, as well as on the relative timescales of these processes (e.g. Bergin et al. 1998; Flower & Pineau des Forêts 2010).

Observations obtained with the Infrared Space Observatory (ISO) have been the first to detect  $\text{H}_2\text{O}$  emissions from states of relatively high excitation ( $T_{\text{kin}} \sim 500\text{--}1500$  K, e.g. Liseau et al. 1996; Ceccarelli et al. 1998; Nisini et al. 2000). More recently, the SWAS and *Odin* satellites observed the fundamental o- $\text{H}_2\text{O}$  transition at 557 GHz in a sample of outflows (Bjerkeli et al. 2009; Franklin et al. 2008). These observations probed cooler gas than had been observed with ISO, but were able to resolve the line profiles for the first time, demonstrating the association of water emission with the high-velocity gas. These studies provided the first determinations of the water abundance, yielding values in the range  $\sim 10^{-7}$  to  $\sim 10^{-4}$  and suggesting that the  $\text{H}_2\text{O}$  abundance depends on the gas temperature and speed (Franklin et al. 2008; Giannini et al. 2001). However, the strength of this conclusion was limited by the large beam sizes used in these previous observations, together with their limited spectral resolution and/or excitation coverage; these limitations made it difficult to associate enhanced abundances or broadened line profiles with specific regions along the outflows or to infer whether these globally averaged properties are really representative of the physical and chemical conditions in specific regions of shock activity.

*Herschel* (Pilbratt et al. 2010) represents the natural evolution for the study of  $\text{H}_2\text{O}$  in protostellar sources, thanks to the combination of much improved spectral/spatial resolution and sensitivity provided by the Photodetecting Array Camera and Spectrometer (PACS, Poglitsch et al. 2010) and Heterodyne Instrument for the Far Infrared (HIFI, de Graauw et al. 2010) instruments. In the framework of the “Water In Star-forming regions with *Herschel*” (WISH, van Dishoeck et al. 2011) key program, we have undertaken systematic PACS and HIFI observations of young outflows in nearby clouds. Within this program, studies of individual shocks have been published in Bjerkeli et al. (2011), Santangelo et al. (2012), Vasta et al. (2012), and Tafalla et al. (2012), while water maps of the L1157 and VLA1623 outflows have been presented in Nisini et al. (2010) and Bjerkeli et al. (2012). All these studies complement observations at the central source position, which probe outflowing gas shocked in the inner jet and envelope cavity walls (Kristensen et al. 2012; Herczeg et al. 2011; Kaska et al. 2012; Goicoechea et al. 2012).

This paper focuses on PACS and HIFI mapping observations of the outflow from the class 0 source L1448-C (also named L1448-mm). This is a low-luminosity ( $L = 7.5 L_{\odot}$ ; Tobin et al. 2007) protostellar source located in the Perseus Molecular Cloud ( $D = 232$  pc; Hirota et al. 2011), which drives a powerful and highly collimated flow that has been detected through interferometric CO and SiO observations (Guilloteau et al. 1992; Bachiller et al. 1995; Hirano et al. 2010). To the north, the L1448-C outflow interacts with two more compact

flows that originate from a small cluster of three young sources (L1448-NA, NB and NW, Looney et al. 2000).

Regions of shocked gas are seen along the entire outflow by means of near- and mid-IR molecular hydrogen emission (Davis & Smith 2006; Neufeld et al. 2009; Giannini et al. 2011), which indicate the presence of a gas in a wide range of temperatures, from  $\sim 300$  to more than 2000 K. ISO detected a far-IR spectrum rich in  $\text{H}_2\text{O}$  and CO transitions toward the L1448-C outflow (Nisini et al. 1999, 2000). The analysis of these lines constrained their emission as coming from warm gas with an enhanced water abundance, as predicted by models for nondissociative shocks. SWAS and *Odin* detected the 557 GHz line but at a single-to-noise ratio that was too low to characterize its emission kinematically. These studies, however, suggest that this line might probe a colder water gas component whose abundance is less enhanced with respect to the warm gas (Benedettini et al. 2002). HDO emission at 80.6 GHz has also been detected toward L1448-C, and is associated with the protostar and the shocked walls of the outflow cavity (Codella et al. 2010b).

Within the WISH program, the L1448-C outflow has been the subject of a detailed study that includes a survey of several lines at specific positions in addition to the mapping observations presented here. In particular, *Herschel*-HIFI observations of the central L1448-C source have been reported by Kristensen et al. (2011), who detected prominent emission originating from a broad velocity component, probably associated with the interaction of the outflow with the protostellar envelope, and from the extreme high-velocity gas (EHV, the so-called “bullets”) associated with the collimated molecular jet. Santangelo et al. (2012) discussed HIFI observations carried out toward two specific shock spots and showed that  $\text{H}_2\text{O}$  line profiles change significantly with excitation, indicating the presence of gas components having different physical conditions.

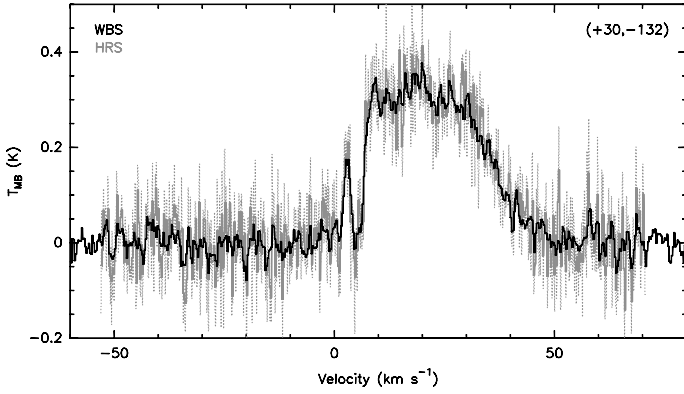
The main aims of this work will be to define the global morphological and kinematical properties of the  $\text{H}_2\text{O}$  emission in comparison with other standard outflow and shock tracers and to study abundance variations in the different shocked regions. To this end, complementary CO(3–2) and SiO(8–7) maps of the same region covered by the *Herschel* observations will be presented and discussed.

## 2. Observations

### 2.1. PACS observations

Observations with the PACS instrument were performed on 27 February 2010 (with observing identification number OBSID = 1342191349). The PACS integral field unit (IFU) in line spectroscopy mode was used in chopping/nodding mode to obtain a spectral map of the L1448 outflow centered on the  $\text{H}_2\text{O}$   $2_{12}\text{--}1_{01}$  line at  $179.527\text{ }\mu\text{m}$  (i.e. 1669.905 GHz, hereafter referred to as the “179  $\mu\text{m}$  line”). The IFU consists of a  $5 \times 5$  pixel array providing a spatial sampling of  $9''.4/\text{pixel}$ , for a total field of view of  $47'' \times 47''$ . The diffraction-limited full width at half maximum (FWHM) beam size at 179  $\mu\text{m}$  is  $12''.6$ . The L1448 outflow region (about  $5' \times 2'$  centered on the L1448-C(N) source,  $\alpha(\text{J2000}) = 03^{\text{h}}25^{\text{m}}38.4^{\text{s}}$ ,  $\delta(\text{J2000}) = +30^{\circ}44'06''$ ) was covered through a single Nyquist-sampled raster map, arranged along the outflow axis. The *Herschel* pointing accuracy is  $\sim 2''$ .

The spectral resolution at 179  $\mu\text{m}$  is  $R \sim 1500$  (i.e.  $\sim 210\text{ km s}^{-1}$ ). The observation was performed with a single scan cycle, providing an integration time per spectral resolution element of 30 s. The total on-source time for the entire map was 5670 s.



**Fig. 1.** Comparison between a WBS and HRS spectrum at a representative position in the outflow (offsets in arcsec with respect to L1448-C are indicated). Full black lines show the WBS data, while the gray dotted and full lines show the HRS data before and after smoothing to the WBS resolution, respectively.

The data were reduced with HIPE<sup>1</sup> v6.0, where they were flat-fielded and flux-calibrated by comparison with observations of Neptune. The calibration uncertainty amounts to around 20–30%, based on cross-calibrations with HIFI and PACS continuum photometry (internal WISH report). Finally, in-house IDL routines were used to locally fit and remove the continuum emission and to construct an integrated line map.

## 2.2. HIFI observations

A region of  $5' \times 2'$  oriented along the direction of the L1448 outflow (PA  $164^\circ$ ) was mapped in the  $\text{H}_2\text{O } 1_{10-1_{01}}$  line at 556.936 GHz (i.e.  $538.29 \mu\text{m}$ , hereafter “the 557 GHz line”) with the HIFI instrument on 19 August 2010 (OBSID: 1342203200). The on-the-fly (OTF) mode was adopted, with a distance between adjacent scans of  $16''$ , slightly less than half the diffraction HPBW (which is  $38''$  at the observed line frequency). The observations were performed in band 1b with both the Wide Band (resolution 1.1 MHz) and High Resolution (resolution 0.25 MHz) Spectrograph backends (WBS and HRS, respectively), for a total on-source integration time of 3981 s. An inspection of the two sets of data showed that the HRS spectra fail to provide additional information on the line velocity structure, and, furthermore, result in a higher rms noise when smoothed to the resolution of the WBS data (see an example in Fig. 1). Hence we only used the WBS data here. The data were reduced using HIPE v7, while the analysis was performed using the GILDAS<sup>2</sup> package. Calibration of the raw data onto the  $T_A$  scale was performed by the in-orbit system, while the spectra were converted to a  $T_{\text{mb}}$  scale adopting a main beam efficiency  $\eta_{\text{mb}} = 0.75$  (Roelfsema et al. 2012).

Additional analysis consisted of baseline removal in each individual spectrum, averaging of spectra taken during different cycles, and construction of a final data-cube sampled at a regular grid with a half-beam spacing. Observations from the H and V polarizations were separately reduced: spectra from the two polarizations were acquired at slightly different coordinates (offset of  $\sim 7''$ ) that were taken into account in constructing the final

regridded map. The rms noise achieved in the final data-cube is typically about  $T_{\text{mb}} \sim 0.02$  K in a  $1 \text{ km s}^{-1}$  bin.

## 2.3. JCMT-HARP observations

Complementary CO(3–2) and SiO(8–7) OTF maps were obtained in January 2009 with the HARP-B heterodyne array (Smith et al. 2008) and ACSIS correlator (Dent et al. 2000) on the James Clerk Maxwell Telescope (JCMT). The rest frequencies are 345 796.0 and 347 330.6 GHz for CO(3–2) and SiO(8–7), respectively (Pickett et al. 1998). The mapped area was covered by consecutive scans in basket-weave mode at a position angle of  $160^\circ$ . Each scan was offset by  $29'.1$  in the orthogonal direction, and the signal was integrated every  $7'.3$  (half HPBW, about  $14''$ ) along the scan direction. We observed in standard position-switched observing mode, with an off-source position at  $(+140'', 0'')$ , chosen to be devoid of sources and the presence of high-velocity gas. Single maps were co-added and initial data cubes converted into GILDAS format for baseline subtraction and subsequent data analysis. The resulting map is centered on  $\alpha_{\text{J2000}} = 03^{\text{h}}25^{\text{m}}38^{\text{s}}.9$   $\delta_{\text{J2000}} = +30^\circ44'05''.0$ , and it has dimensions of  $300'' \times 116''$ .

The observed bandwidth, 1 GHz, was sampled with 2048 channels for a spectral resolution of 488 kHz, which corresponds to  $0.42 \text{ km s}^{-1}$  at the observed frequencies. The spectra were smoothed to  $1 \text{ km s}^{-1}$  resolution to increase the sensitivity and converted to the main-beam brightness temperature ( $T_{\text{mb}}$ ) scale adopting a main-beam efficiency ( $\eta_{\text{mb}}$ ) of 0.6. The mean rms noise in  $T_{\text{mb}}$  is around 100 mK and 80 mK for CO(3–2) and SiO(8–7), respectively.

## 3. Results

### 3.1. $\text{H}_2\text{O}$ morphology

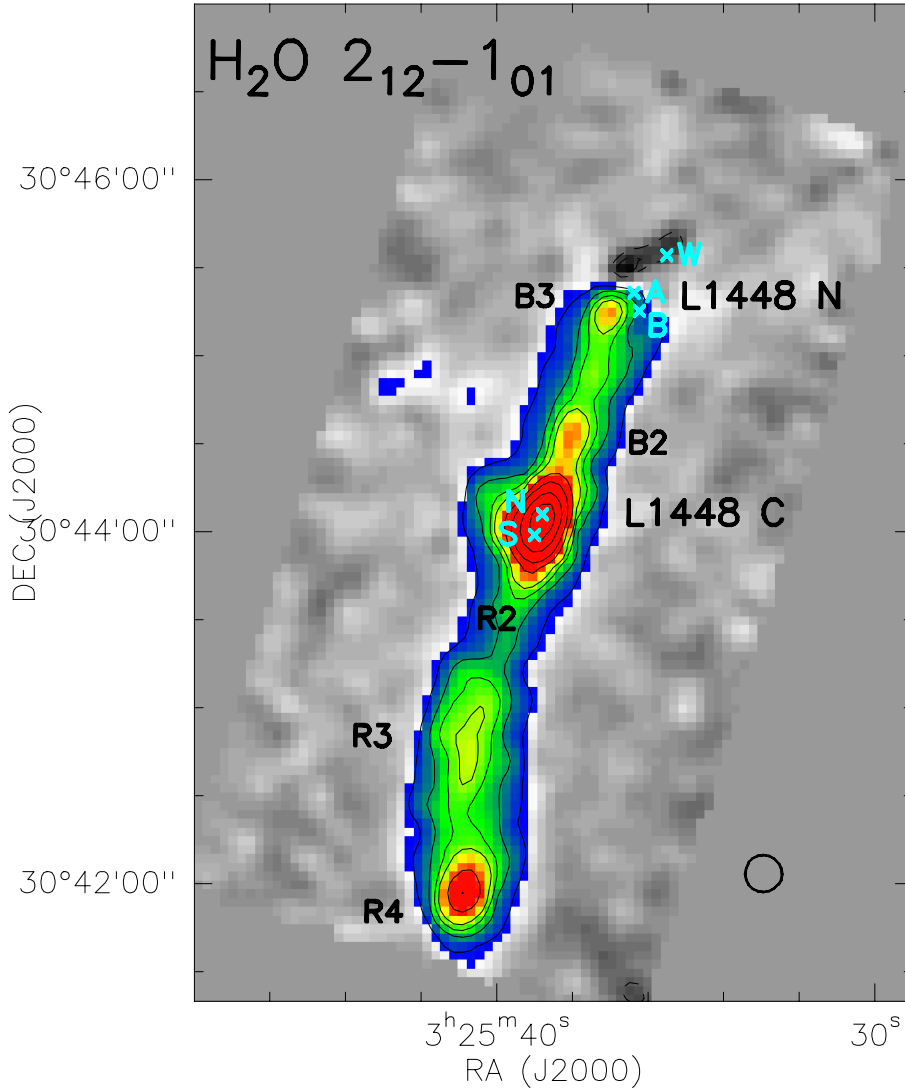
The PACS line map displayed in Fig. 2 shows that the  $179 \mu\text{m}$  emission is confined along the L1448-C outflow, with emission peaks roughly located at the positions of shocked spots previously identified through CO and SiO observations; these are named, following the nomenclature of Bachiller et al. (1990), R1 to R4 and B1 to B3 for the redshifted and blueshifted lobes, respectively. The strongest peak is observed toward the central position, where two IR sources, L1448-C(S) and C(N), are located (Jørgensen et al. 2006). Another strong emission peak is also observed in the terminal part of the redshifted lobe (knot R4). To the north, three different protostellar sources are present, resolved by mm interferometric observations and called A, B, and W, following Looney et al. (2000) and Kwon et al. (2006).  $\text{H}_2\text{O}$  emission ends abruptly at the position of L1449 N(A) and N(B), while a lane of water in absorption is seen toward L1448 N(W). Noticeably, and in contrast to what is observed at the central position, no emission is associated with any of the three L1448 N sources. Given the low spectral resolution of the PACS observations, there could be a mixture of emission and absorption beyond the B2 knot that causes a near cancellation of the emission. Figure 3 shows the line brightness profile along the flow, obtained by integrating the intensity in a region with a width of about  $30''$  perpendicular to the outflow axis. This plot shows the relative intensities of the different emission peaks, indicating that the emission is extended but clumpy.

In the same figure, bottom panel, an enlargement around the L1448-C source is displayed, where the  $179 \mu\text{m}$  line and continuum intensity profiles are compared. In the continuum, the two sources C(S) and C(N) are spatially unresolved: the FWHM of

<sup>1</sup> HIPE is a joint development by the *Herschel* Science Ground Segment Consortium, consisting of ESA, the NASA *Herschel* Science Center, and the HIFI, PACS and SPIRE consortia.

<sup>2</sup> <http://www.iram.fr/IRAMFR/GILDAS/>





**Fig. 2.** Continuum-subtracted PACS map of the integrated  $\text{H}_2\text{O}$   $2_{12}-1_{01}$  emission along the L1448 outflow. Sources in the region are indicated with crosses: L1448-C(S) and C(N) in the central region, and L1448 NA, NB, and NW in the northern region. The diffraction-limited beam of  $FWHM$   $12.6''$  is also indicated. The different emission peaks are labeled following the nomenclature adopted by Bachiller et al. (1990) for individual CO peaks. The average rms noise in the observed region is of about  $2 \times 10^{-6} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$ . Contours are drawn at  $3\sigma$ ,  $6\sigma$ ,  $9\sigma$ ,  $12\sigma$ ,  $16\sigma$ ,  $30\sigma$ ,  $50\sigma$ , and  $75\sigma$ . Negative contours are indicated by dashed lines.

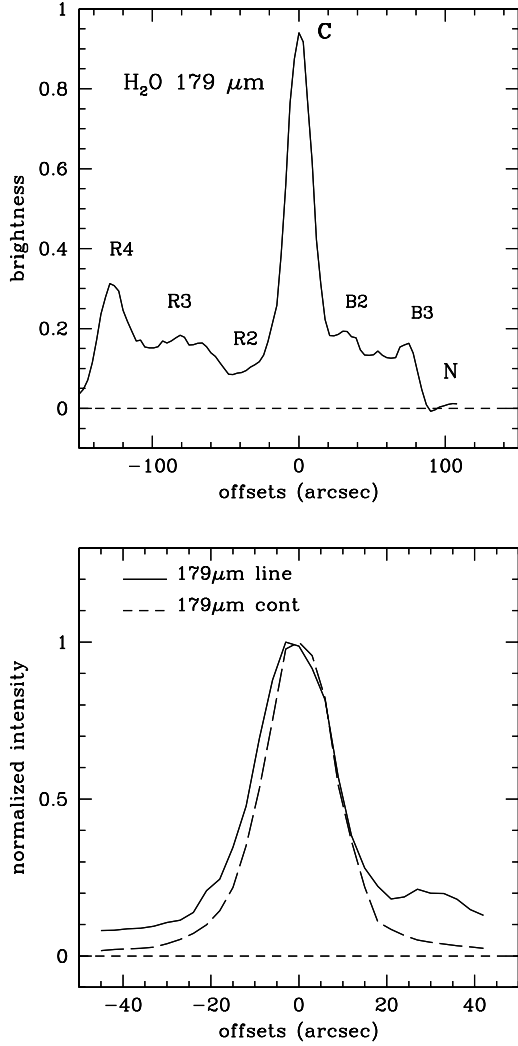
the spatial profile, when fitted with a Gaussian, is  $\sim 18''$ , which means a deconvolved size of  $\sim 13''$ , assuming both the beam and the emitting region to be Gaussian. For comparison, the two sources have a separation of about  $8''$ . The line emission appears to be slightly extended with respect to the continuum, with a deconvolved  $FWHM$  of about  $15''$ . This is roughly similar to the extension of the inner EHV SiO jet as observed, for example, by Guilloteau et al. (1992) and Hirano et al. (2010; their knots B1/R1). A more detailed description of the water morphology in comparison with other tracers in the regions around the C and N sources is given in Appendix A.

Figure 4, right panel, presents a comparison of the  $179 \mu\text{m}$  emission, shown as a gray-scale image, with the integrated  $\text{H}_2\text{O}$   $557 \text{ GHz}$  emission, displayed by separate contours for the blue- and redshifted emission. The two lines show a similar morphology compatible with the much lower spatial resolution of the HIFI spectra. Indeed, as in the PACS data, bright emission is observed toward the central L1448-C position and the southern redshifted outflow lobe, while no water emission is detected north of the L1448-N position. The complete set of HIFI data are presented in Fig. B.1, where all spectra are displayed in a regular grid. The comparison between the water and CO peaks can be directly visualized in Fig. 4, left panel, where the  $179 \mu\text{m}$  line map is overlaid with contours of the CO(3–2) emission, separated into the blue- and redshifted gas. Along the southern outflow,

the CO emission is systematically shifted with respect to  $\text{H}_2\text{O}$ . In the northern region, CO extends farthest to the north, where the outflow from the C(N) source is confused with a second outflow (at PA roughly  $110^\circ$ ) emerging from the N(B) source (Bachiller et al. 1990, see next subsection). Therefore, although water roughly follows the direction of the CO outflow, there is no strict correlation between individual emission peaks.

### 3.2. $\text{H}_2\text{O}$ kinematics

HIFI  $557 \text{ GHz}$  line profiles at selected positions along the outflows are shown in Fig. 5 and are compared with the CO(3–2) line. To make the comparison independent of beam filling effects, the CO(3–2) lines were extracted from a map convolved to the same spatial resolution as the  $\text{H}_2\text{O}$   $557 \text{ GHz}$  observations. All lines show narrow absorption at the systemic velocity due to foreground gas. The  $557 \text{ GHz}$  line always traces the same range of velocity as CO. Maximum velocities up to  $50 \text{ km s}^{-1}$  are detected in all positions, while velocities reaching up to  $+80 \text{ km s}^{-1}$  are observed at the position of the L1448-C source. Although they trace the same velocity range, the  $\text{H}_2\text{O}$  line profiles are different from those of CO, as already shown in other studies (Santangelo et al. 2012; Kristensen et al. 2011): most of the CO emission is localized at low velocity ( $V_r - V_{\text{LSR}} \lesssim \pm 10 \text{ km s}^{-1}$ ),



**Fig. 3.** *Upper panel:* H<sub>2</sub>O 179  $\mu$ m intensity cut along the L1448 flow, at PA 164°. The normalized intensity is integrated over a width of 30'' perpendicular to the cut. The location of the C(N) source is taken as the reference for the offsets. *Bottom panel:* normalized intensities of the 179  $\mu$ m H<sub>2</sub>O line and continuum around the L1448-C source, along the same cut direction as above.

while the bulk of the water emission occurs at intermediate velocities ( $V_r - V_{\text{LSR}} \sim 5\text{--}30 \text{ km s}^{-1}$ ).

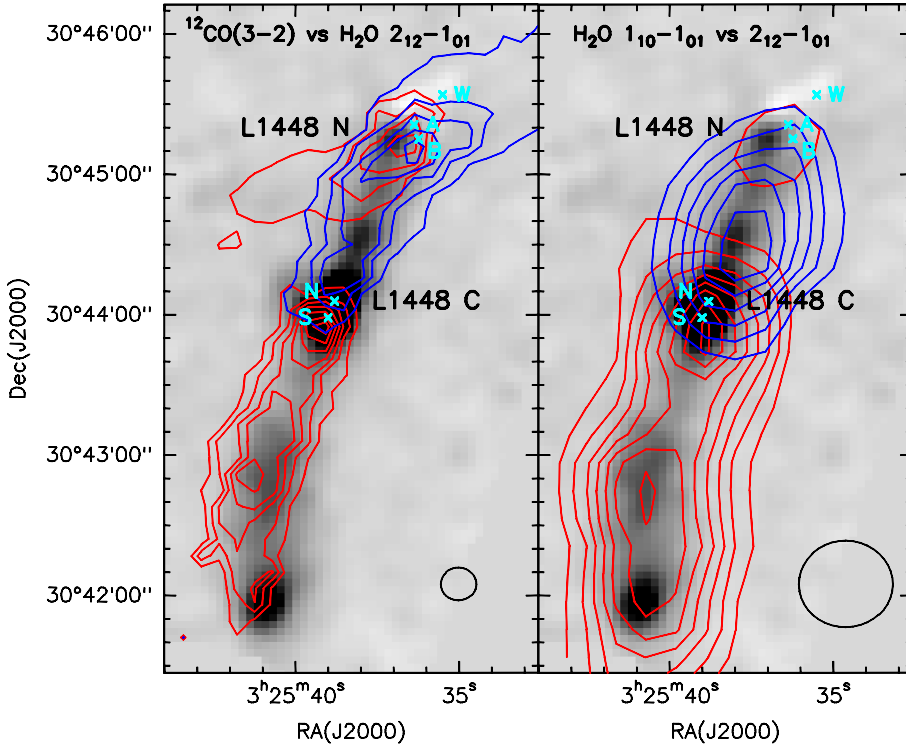
A detailed view of the H<sub>2</sub>O and CO emission spatial distribution as a function of velocity can be visualized in the velocity channel maps presented in Fig. B.2. Figure 7 shows the maps of the two emissions integrated in three representative velocity intervals, corresponding to the low ( $\pm 1\text{--}10 \text{ km s}^{-1}$ ), intermediate ( $\pm 11\text{--}45 \text{ km s}^{-1}$ ), and high ( $\pm 46\text{--}86 \text{ km s}^{-1}$ ) velocity gas. Emission at the low and intermediate velocities is detected all along the outflow, with the exception, as already noted from the PACS map, of the region northwest of the L1448-N sources, where water is absent while CO is detected. Figure 7 also shows that both H<sub>2</sub>O and CO in the high-velocity range ( $\geq 50 \text{ km s}^{-1}$ ) are not confined at the central source position, but extend between  $-100$  and  $+50$  arcsec from L1448-C. If we look at the individual spectra shown in Fig. 5, we see that in the CO profiles this EHV gas always appears as a separate “bullet” emission superimposed on the line wing at lower velocity (e.g. Bachiller et al. 1990). These EHV bullets are physically

associated with the highly collimated molecular jet displaced along the outflow axis (e.g. Hirano et al. 2010). Water emission kinematically associated with these bullets is clearly detected only toward the central L1448-C region (see Fig. 6) and has been discussed in Kristensen et al. (2011). Although EHV emission is also detected at greater distances from the source in CO, this emission does not appear as a separate bullet component in the individual H<sub>2</sub>O spectra, but rather as an extension of the low-velocity component wing. Hence the contribution of the EHV gas to the total H<sub>2</sub>O line emission is lower than in the case of CO. This will be discussed in more detail in the next section.

### 3.3. H<sub>2</sub>-to-CO ratio vs. velocity

As seen in the previous section, the water and CO profiles look different, and thus their ratio varies significantly with velocity as illustrated in Fig. 5. At all selected outflow positions, the H<sub>2</sub>O  $1_{10\text{--}1_{01}}$ /CO(3–2) ratio increases with velocity up to  $v \lesssim 20 \text{ km s}^{-1}$ : this is a trend that was identified previously in all sources observed in the 557 GHz line by SWAS and *Herschel* (Franklin et al. 2008; Kristensen et al. 2012). Given the high signal-to-noise ratio reached in our observations at high velocity, we can now see that beyond  $20 \text{ km s}^{-1}$  the ratio reaches a plateau and then decreases again at the highest velocities. Variations of the H<sub>2</sub>O/CO line ratio could be caused by variations in the physical conditions with velocity and/or abundance variations. In addition, at velocities close to the ambient velocity, a different degree of absorption of the two lines by the cold gas may influence this ratio. The increase in the H<sub>2</sub>O/CO ratio as a function of velocity has so far been interpreted as an increase of the H<sub>2</sub>O abundance at high speeds; assuming the same temperature and density conditions for the two lines, Franklin et al. (2008) derived an H<sub>2</sub>O abundance in the gas with  $V_{\text{max}} \sim 20 \text{ km s}^{-1}$  an order of magnitude higher than that in the low-velocity gas. This conclusion, however, was based on an erroneous assumption, since different physical conditions pertain to CO and H<sub>2</sub>O; moreover, the physical conditions change with velocity, as shown in, e.g., Santangelo et al. (2012); Vasta et al. (2012); Lefloch et al. (2010).

Furthermore, the decrease of the H<sub>2</sub>O/CO line ratio at velocities higher than  $\sim 30\text{--}40 \text{ km s}^{-1}$  contradicts the conclusion that a higher water abundance is always associated with the gas at the highest velocity. The drop in the H<sub>2</sub>O/CO line ratio roughly coincides with the velocity range of the EHV bullet emission, indicating that a critical change in the physical and/or chemical conditions occurs in the bullets with respect to the “standard” wing emission. Tafalla et al. (2010) studied the chemical composition of the EHV gas in L1448, comparing it with the gas responsible for the wing emission, and found significant differences between these two components. They found, in particular, that the EHV gas is relatively rich in O-bearing species and poor in C-bearing molecules compared to the wing regime. Thus the observed drop in the H<sub>2</sub>O  $1_{10\text{--}1_{01}}$ /CO(3–2) ratio in the EHV regime is more easily understood if the water-emitting EHV gas has a lower temperature and/or density than the gas responsible for the wing emission. Kristensen et al. (2011) compared the excitation conditions for water in the EHV gas with those responsible for the wing emission toward the central position, but were unable to identify significant differences in the two regimes. Santangelo et al. (2012), on the other hand, found that at the L1448-R4 position the high-velocity H<sub>2</sub>O emission is associated with gas at a density about an order of magnitude lower than that of the gas responsible for the low-velocity emission.



**Fig. 4.** Overlay of the JCMT  $^{12}\text{CO}(3-2)$  (left panel) and HIFI  $\text{H}_2\text{O}$  557 GHz (right panel) emission on the  $\text{H}_2\text{O}$  179  $\mu\text{m}$  map. The blue and red contours represent emission integrated in the velocity ranges  $(-100, +4)$  and  $(+6, +100)$   $\text{km s}^{-1}$ , respectively. Contours are drawn from 25 to 200  $\text{K km s}^{-1}$ , with steps of 20  $\text{K km s}^{-1}$ , for the  $\text{CO}(3-2)$  map, and from 2 to 12  $\text{K km s}^{-1}$ , with steps of 1.2  $\text{K km s}^{-1}$ , for the  $\text{H}_2\text{O}$  557 GHz map. The HPBW of 14'' (JCMT) and 38'' (HIFI) is indicated.

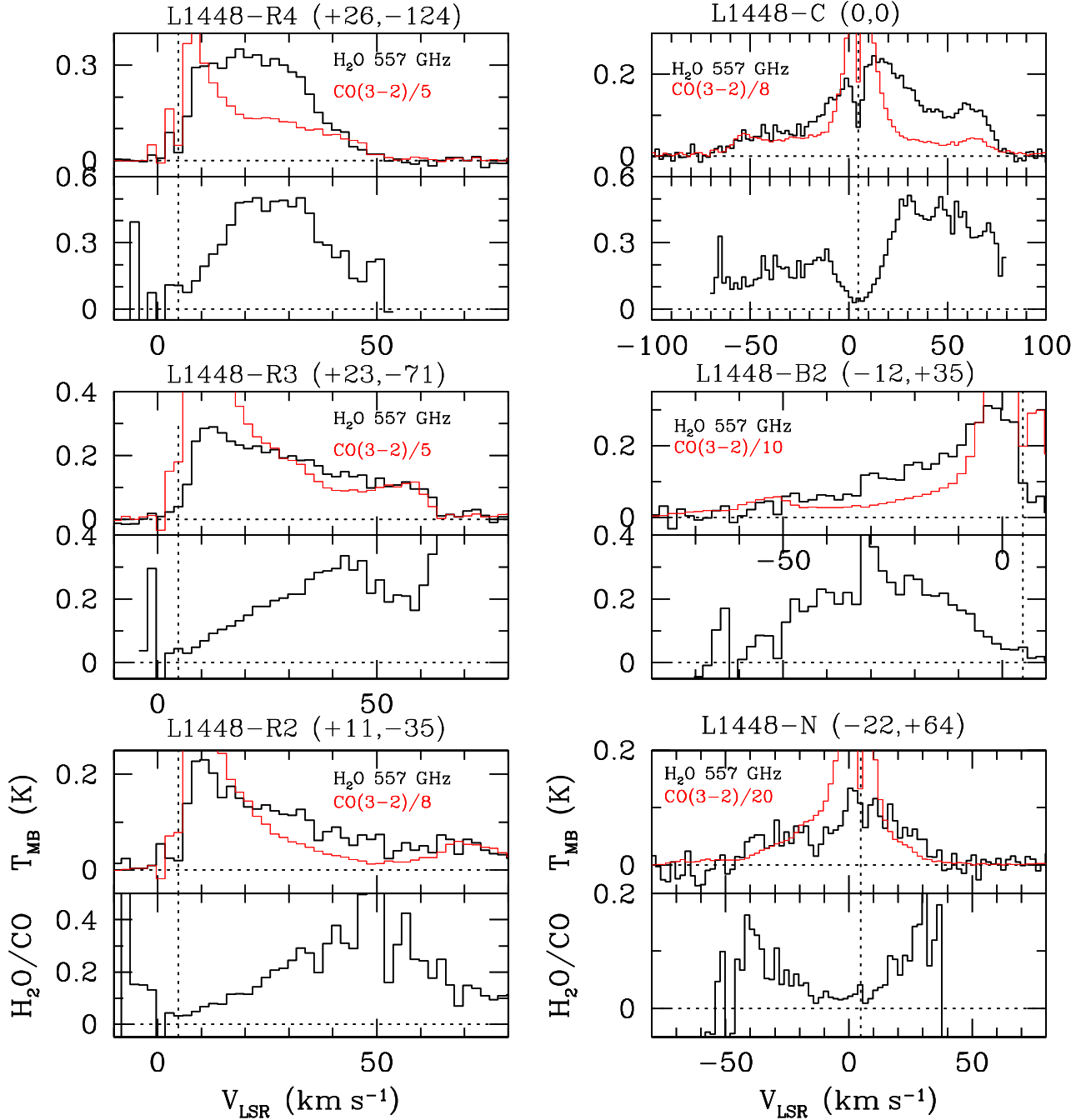
### 3.4. SiO and $\text{H}_2\text{O}$

The  $\text{SiO}(8-7)$  map, obtained together with the  $\text{CO}(3-2)$  observations, only shows emission close to the central position, where it can be associated with the L1448-C molecular jet (Hirano et al. 2010). In fact, while  $\text{SiO}$  emission from the  $(1-0)$  and  $(2-1)$  transitions is observed along the entire molecular outflow, peaking at the different clump positions (Bachiller et al. 1991; Dutrey et al. 1997), lines at higher excitation are observed only toward the highly collimated micro-jet (Bachiller et al. 1991; Nisini et al. 2007). The comparison of the  $\text{SiO}$  and  $\text{H}_2\text{O}$  emissions (see Fig. 6) shows that their profiles are strikingly different. The EHV bullets are more prominent in  $\text{SiO}$  than in  $\text{H}_2\text{O}$ : conversely, no  $\text{SiO}$  is associated with the strong intermediate velocity broad  $\text{H}_2\text{O}$  emission peaking around the ambient velocity. The association of  $\text{SiO}$  emission with the EHV collimated jet is a well-known feature characteristic of several class 0 sources (e.g. Hirano et al. 2006; Codella et al. 2007); it has been suggested that  $\text{SiO}$  in the jet is either directly synthesized in the dust-free jet acceleration region (Glassgold et al. 1991; Panoglou et al. 2011) or originates in shocked ambient material where silicon is released into the gas phase by the disruption of grain cores (e.g. Gusdorf et al. 2008).

An origin in the primary jet has recently been supported by both interferometric observations in the HH212 object (Cabrit et al. 2007) and by the molecular survey conducted on the L1448-R2 EHV bullet by Tafalla et al. (2010), who showed that the bullets possess a peculiar chemistry with respect to the standard outflow wing emission, suggesting an origin different from shocks. The fact that  $\text{SiO}(8-7)$  is more prominent than  $\text{H}_2\text{O}$  557 GHz in the EHV bullets may either be an excitation effect or the result of an enhanced  $\text{SiO}/\text{H}_2\text{O}$  abundance ratio, or both. The excitation of  $\text{SiO}$  in the EHV bullets has been studied by Nisini et al. (2007), who found that the  $\text{SiO}$ -emitting gas has a density  $\sim 10^6 \text{ cm}^{-3}$  and  $T_{\text{kin}} \gtrsim 300 \text{ K}$ . Kristensen et al. (2011) found that similar conditions may be consistent also with the water emission in the bullets, suggesting that  $\text{SiO}$  and  $\text{H}_2\text{O}$

are excited in the same gas. With this assumption, the observed  $\text{H}_2\text{O}$  557 GHz/  $\text{SiO}(8-7)$  intensity ratio in the bullets implies a  $\text{H}_2\text{O}/\text{SiO}$  abundance ratio of  $\sim 10$ . Shock models that take the erosion of Si from grain cores and mantles into account predict this ratio to be about  $10^3$  or more, depending on the shock velocity (Gusdorf et al. 2008; Jiménez-Serra et al. 2008). On the other hand, a  $\text{H}_2\text{O}/\text{SiO}$  ratio of about 10 is predicted by the wind model of Glassgold et al. (1991) where  $\text{H}_2\text{O}$  and  $\text{SiO}$  are formed in dust-free gas directly ejected from the protostar, provided that the mass loss rate of the spherical wind is  $>10^{-5} M_{\odot} \text{ yr}^{-1}$ . Only high mass loss rates like this yield a density at the wind base that is sufficiently high to permit efficient  $\text{SiO}$  synthesis through gas-phase reactions. Indeed, timescales for  $\text{SiO}$  production are rather low, i.e. they stay below  $10^2 \text{ yr}$ , for  $T > 400 \text{ K}$ , only if the gas density is  $\gtrsim 10^7-10^8 \text{ cm}^{-3}$ . Dionatos et al. (2009) measured a molecular mass flux rate of  $\sim 10^{-7} M_{\odot} \text{ yr}^{-1}$  for the L1448 jet: for this low mass loss value, the model by Glassgold et al. (1991) predicts a negligible abundance of both  $\text{SiO}$  and  $\text{H}_2\text{O}$ . However, given the high collimation of the L1448 jet, the mass loss rate values are not directly comparable and it certainly cannot be ruled out that the two molecules trace the primary jet. In this respect, initial results presented in Panoglou et al. (2011) for the molecular survival in disk winds seem promising, predicting that a significant fraction of water is synthesized in jets from class 0 sources with a mass accretion rate of  $5 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ , implying a mass flux rate of about that measured in L1448. Finally, we note that the timescales to increase the water abundance to values  $X(\text{H}_2\text{O}) > 10^{-5}$  in a gas with  $T > 400 \text{ K}$  are about 100 yr (Bergin et al. 1998), which agrees well with the dynamical timescale for the L1448 jet propagation of about  $\sim 150 \text{ yr}$  (Hirano et al. 2010).

With regard to the broad  $\text{H}_2\text{O}$  emission at intermediate velocities, Kristensen et al. (2011) suggested an origin in shocks caused by the interaction between the outflow and the envelope. Such shocks would be expected to produce significant  $\text{SiO}$  emission, since the disruption of grain cores occurs at shock speeds  $\gtrsim 25-30 \text{ km s}^{-1}$  (Jiménez-Serra et al. 2008; Gusdorf et al. 2008). The efficiency of sputtering and grain-grain collisions, however,



**Fig. 5.**  $\text{H}_2\text{O}$   $1_{10-1_{01}}$  (black) and  $\text{CO}(3-2)$  (red) line profiles at selected outflow positions. CO line profiles, convolved to the  $\text{H}_2\text{O}$  spatial resolution, are scaled to match the  $\text{H}_2\text{O}$  line wings and the corresponding scaling factor is indicated in each plot. At the bottom of each spectrum, the relative  $\text{H}_2\text{O}/\text{CO}$  intensity ratio is plotted as a function of velocity.

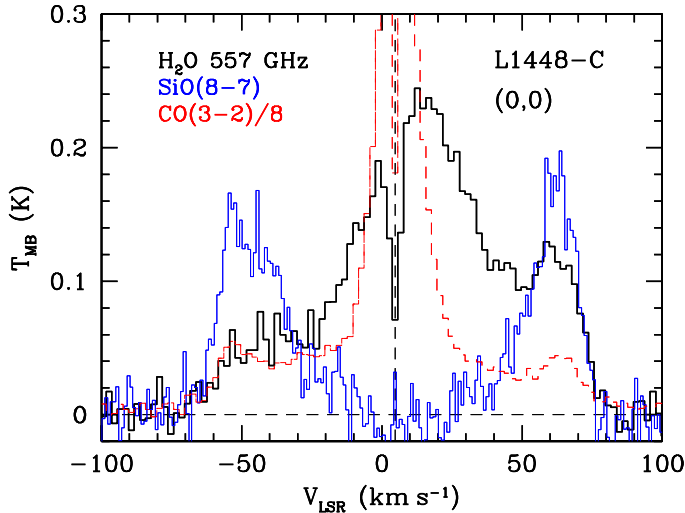
depends on the type of grains involved and on the total density: for large grains, sputtering can be significantly inhibited for  $n(\text{H}_2) \gtrsim 10^6 \text{ cm}^{-3}$ , due to the decrease of the relative velocity between grains and neutral species at these densities (Caselli et al. 1997). In fact, the observed  $\text{SiO}(8-7)$  emission gradually rises from the ambient velocity up to the EHV regime, a behavior that could suggest a progressive enhancement of the  $\text{SiO}$  abundance moving from the regime of high density and low velocity to that of low density and high velocity; the water, on the other hand, can be efficiently produced even at low shock speeds and high densities from sputtering of icy grain mantles, which would explain the different behavior of the two species in the intermediate

velocity regime. However, the non-detection toward L1448-C of broad lines from other molecules that reside on ices, such as  $\text{CH}_3\text{OH}$  (Jiménez-Serra et al. 2005), is indicative of the fact that the gas/grain chemistry can indeed be more complex than normally assumed.

#### 4. $\text{H}_2\text{O}$ physical conditions and abundances

From the relative and absolute intensities of the observed  $\text{H}_2\text{O}$  lines, it is possible to derive spatially and spectrally averaged information about their excitation conditions. For this purpose, we convolved the PACS line map at the HIFI 557 GHz resolution





**Fig. 6.** Overlay between H<sub>2</sub>O  $1_{10-1_{01}}$  (black), SiO(8–7) (blue) and CO(3–2) (red) toward the L1448-C position.

(i.e. 38'') and integrated the HIFI spectra over velocity to compare line intensities for the same spatial and spectral regions. In Table 1, we report these intensities, as measured at different positions along the outflow, which correspond roughly to the water intensity peaks.

In Fig. 8, the 179  $\mu$ m intensity is plotted as a function of the 179  $\mu$ m/557 GHz ratio. Here the observed values are confronted with predictions obtained using the RADEX code (van der Tak et al. 2007) that we ran using the large velocity gradient (LVG) approximation in plane-parallel geometry. Based on the analysis presented in Santangelo et al. (2012), Vasta et al. (2012), and Bjerkeli et al. (2012), we assumed that the kinetic temperature ( $T_{\text{kin}}$ ) of the gas traced by the observed H<sub>2</sub>O transitions is in the range 300–500 K, similar to that derived by Giannini et al. (2011) from *Spitzer* observations of the low-lying H<sub>2</sub> transitions. We then explored hydrogen densities ( $n(\text{H}_2)$ ) in the range  $10^5$ – $10^7$  cm<sup>-3</sup> and o-H<sub>2</sub>O column densities in the range  $10^{12}$ – $10^{16}$  cm<sup>-2</sup>. A linewidth of 30 km s<sup>-1</sup> was adopted, representing the typical FWHM of the observed 557 GHz line.

In Fig. 8 H<sub>2</sub>O 179  $\mu$ m intensities, convolved to the 557 GHz resolution, are indicated as open (cyan) symbols, while filled (red) symbols indicate the unconvolved PACS intensities. The convolved and unconvolved intensities differ by factors between 1.2 and 5, reflecting the extended but clumpy nature of the 179  $\mu$ m emission as shown in Fig. 3. Assuming that the unconvolved intensities are not additionally diluted within the PACS beam, Fig. 8 suggests that the density of the gas responsible for the H<sub>2</sub>O emission is in the range  $\sim 10^6$ – $10^7$  cm<sup>-3</sup> while the H<sub>2</sub>O column density is  $\geq 10^{13}$  cm<sup>-2</sup>.

This result is consistent with the work of Santangelo et al. (2012), who analyzed *Herschel*-HIFI spectra of several H<sub>2</sub>O lines gathered toward the L1448-R4 and B2 positions, concluding that the water emission in these positions arises from a gas at  $T \sim 400$ – $600$  K and density of about  $1$ – $5 \times 10^6$  cm<sup>-3</sup>. Models with densities lower than  $10^6$  cm<sup>-3</sup> were not able to fit all lines observed with HIFI and would require high column densities that are inconsistent with the upper limit on the H<sub>2</sub><sup>18</sup>O observed in the L1448-R4 position. The conditions we derived are also consistent with the results obtained by Tafalla et al. (2012) from an analysis of the o-H<sub>2</sub>O  $1_{10-1_{01}}$  and  $2_{12-1_{01}}$  emissions in a large sample of shocked spots.

In Fig. 9 the H<sub>2</sub>O data are also compared with the CO(3–2) line intensity, which was convolved to the HIFI resolution. The expected 179  $\mu$ m/CO(3–2) ratio was computed for  $N(\text{CO}) = 5 \times 10^{15}$  cm<sup>-2</sup>: this value assumes an average  $N(\text{H}_2)$  column density of  $5 \times 10^{19}$  cm<sup>-2</sup> along the flow (consistent with the column density estimated in Giannini et al. 2011) and a CO abundance of  $10^{-4}$ . The figure shows that the observed data are reproduced by a single gas component only for  $n(\text{H}_2) \sim 10^7$  cm<sup>-3</sup> and  $N(\text{H}_2\text{O}) < 10^{12}$  cm<sup>-2</sup>. As shown above, these conditions are not consistent with intensities of the 179  $\mu$ m emission. We also note that the assumed  $N(\text{CO})$  is only an upper limit on the beam-diluted CO column density in the assumed 38'' aperture, since the  $N(\text{H}_2)$  was estimated over a beam of size  $\sim 10''$ . To be consistent with the observed ratios, a CO column density one or two order of magnitude higher than that assumed here would be required, clearly inconsistent with the H<sub>2</sub> observations. This is further and more quantitative evidence that the CO(3–2) and the water emission originate from gas components with different excitation conditions. The low- $J$  CO is likely related to the cold entrained gas and not directly associated with the high temperature shocked gas. Assuming that the CO emission originates in gas at a temperature of about 100 K and with a density of  $10^4$  cm<sup>-3</sup> (e.g. van Kempen et al. 2009), the contribution of the H<sub>2</sub>O 557 GHz emission from this gas would be negligible (i.e. 1/10 of the observed beam diluted intensity), even assuming a H<sub>2</sub>O/CO abundance  $\sim 1$ .

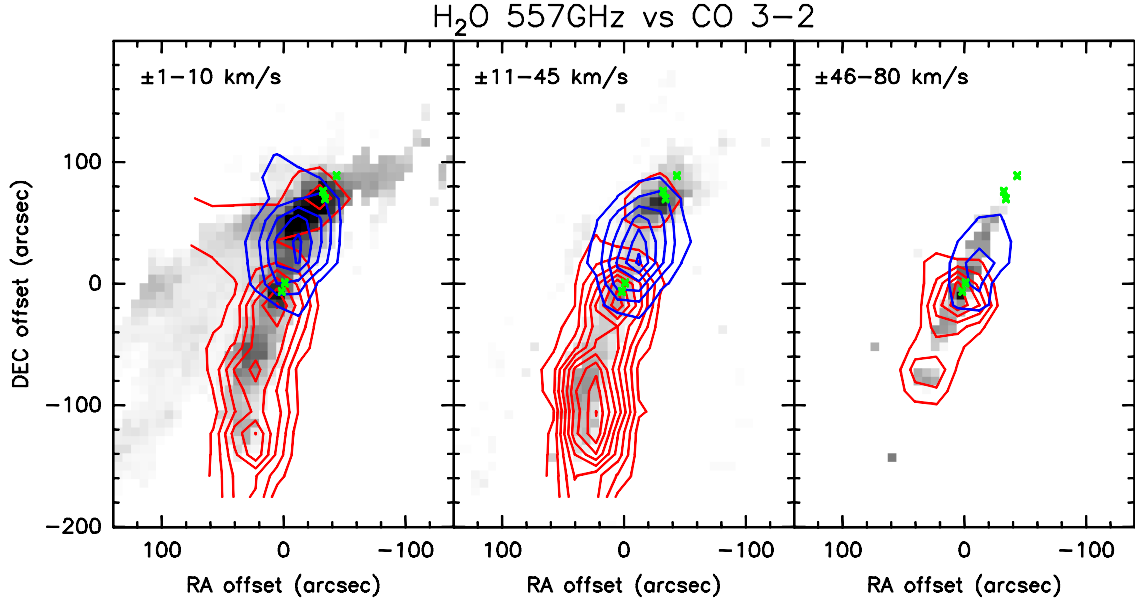
Assuming  $T_{\text{kin}} \sim 500$  K and  $n(\text{H}_2) \sim 5 \times 10^6$  cm<sup>-3</sup>, o-H<sub>2</sub>O beam-diluted PACS column densities are constrained to be about  $10^{13}$  cm<sup>-2</sup> along the flow, while a higher value of about  $10^{14}$  cm<sup>-2</sup> is inferred toward the central position (see Table 1). To estimate the corresponding H<sub>2</sub>O abundance, we derived a  $N(\text{H}_2)$  from the *Spitzer* spectral image of the H<sub>2</sub> S(1) 17  $\mu$ m line (Neufeld et al. 2009; Giannini et al. 2011), on the assumption that it originates in the same gas as seen in H<sub>2</sub>O by PACS. For this purpose, the H<sub>2</sub> 17  $\mu$ m image was convolved to the 12'' resolution of the PACS map, and the beam-averaged  $N(\text{H}_2)$  was determined assuming the line to be in LTE with  $T_{\text{kin}} = 500$  K. Values of  $N(\text{H}_2)$  of about  $0.7$ – $6 \times 10^{19}$  cm<sup>-2</sup> are derived for the different positions. Consequently, the water abundance along the outflow is relatively constant with values  $\sim 0.5$ – $1 \times 10^{-6}$  (see Table 1). For the on-source position, a higher value of  $\sim 10^{-5}$  is found; however, the high on-source extinction might cause the  $N(\text{H}_2)$  column density to be underestimated and consequently the  $X(\text{H}_2\text{O})$  to be overestimated. If we consider as a reference the H<sub>2</sub> S(0) 28  $\mu$ m emission for deriving the  $N(\text{H}_2)$  toward the central position, we obtain a value of  $\sim 5 \times 10^{20}$  cm<sup>-2</sup>, which would imply  $X(\text{H}_2\text{O}) \sim 10^{-6}$ . In this case, we should consider this value as a lower limit, since the S(0) emission is likely dominated by gas colder than that, giving rise to the water emission observed here.

We note that the derived abundances are sensitive to the adopted parameters and assumptions. In the regime considered here, the water column densities that we derive depend almost linearly on the assumed H<sub>2</sub> density, which we estimate to be uncertain by a factor of five. Changes in the assumed temperature, on the other hand, will affect both the H<sub>2</sub>O and the H<sub>2</sub> column densities in a similar fashion, having less impact on the derived H<sub>2</sub>O abundance.

## 5. Origin of the observed emission

Our analysis of the H<sub>2</sub>O  $1_{10-1_{01}}$  and  $2_{12-1_{01}}$  lines suggests that the gas responsible for the bulk of the H<sub>2</sub>O emission is warm, with  $T_{\text{kin}} \sim 300$ – $500$  K, and very dense, with





**Fig. 7.** Contours of the  $\text{H}_2\text{O}$   $1_{10-1_{01}}$  emission integrated in three different velocity intervals, superimposed onto the  $\text{CO}(3-2)$  emission in the same velocity bins (gray scale). The velocity ranges with respect to the systemic velocity of  $V_{\text{LSR}} = 4.7 \text{ km s}^{-1}$ , are shown in the upper side of each panel. Green crosses mark the positions of the different sources (see Fig. 1).

**Table 1.** Line intensities\* and  $\text{H}_2\text{O}$  abundances.

Position (" , ") <sup>a</sup>	$\int T_{\text{mb}} dv \text{ (K km s}^{-1}\text{)}$			$I(10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1})$			$N(\text{o-H}_2\text{O})^b$	$X(\text{H}_2\text{O})^c$
	$\text{H}_2\text{O}$ $1_{10-1_{01}}$	$\text{H}_2\text{O}$ $2_{21-1_{01}}$	$\text{CO}$ $J = 3-2$	$\text{H}_2\text{O}$ $1_{10-1_{01}}$	$\text{H}_2\text{O}$ $2_{21-1_{01}}$	$\text{CO}$ $J = 3-2$	$10^{13} \text{ cm}^{-2}$	$10^{-6}$
(+26.0, -124.1)	10.3	3.2	32.9	1.78	14.9	1.3	3.0	...
(+29.3, -98.2)	7.5	2.8	31.6	1.30	12.9	1.3	1.3	0.7
(+23.4, -71.1)	10.4	2.7	61.3	1.80	12.6	2.5	1.6	0.8
(+11.1, -36.4)	7.9	2.4	26.9	1.37	11.0	1.1	1.0	2
(0, 0)	15.7	8.5	115.6	2.72	39.6	4.7	9.0	1–12.0
(-12.5, +34.9)	9.0	3.0	78.05	1.56	14.5	3.2	1.6	1
(-21.7, +63.9)	5.4	2.1	104.3	0.93	9.49	4.2	1.8	0.4

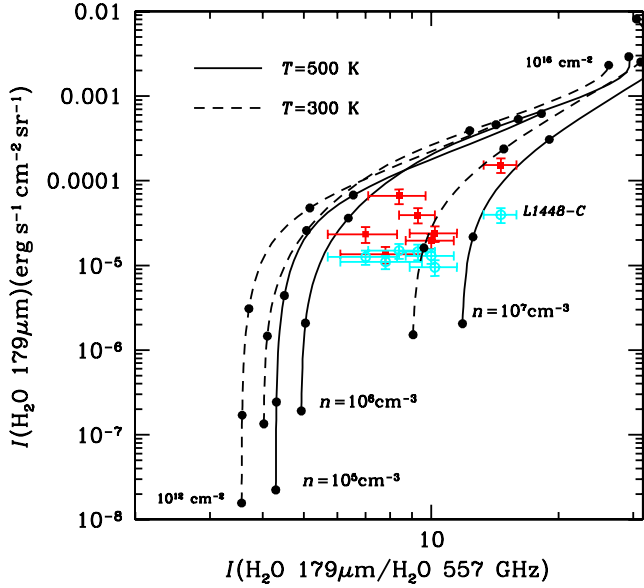
**Notes.** (\*) Intensities measured in a circular area of diameter  $38''$ . Absolute uncertainties are of about 20–30% for  $\text{H}_2\text{O}$  measurements and 15% for  $\text{CO}(3-2)$ . (<sup>a</sup>) Offsets with respect to  $\alpha_{2000} = 03:25:38.8$ ,  $\delta_{2000} = +30:44:04$  (<sup>b</sup>) Derived from the unconvolved  $2_{21-1_{01}}$  line intensity assuming  $T_{\text{kin}} = 500 \text{ K}$  and  $n(\text{H}_2) = 5 \times 10^6 \text{ cm}^{-3}$ . The associated uncertainty is within a factor of 5. (<sup>c</sup>) With respect to the  $\text{H}_2$  column densities derived from the  $\text{S}(1) 17 \mu\text{m}$  line and assuming an o/p ratio of 3. Uncertainty on the abundance is within a factor of 10.

$n(\text{H}_2) \sim 5 \times 10^6 \text{ cm}^{-3}$ . These parameters, as well as the associated low abundance of  $\lesssim 10^{-6}$ , seem to be typical of the excitation traced by the two  $\text{H}_2\text{O}$  transitions, since similar physical conditions have been derived for other outflow positions by several authors (e.g. Bjerkeli et al. 2012; Vasta et al. 2012; Tafalla et al. 2012). These physical conditions, along with the observed spatial distribution of the  $179 \mu\text{m}$  emission, indicate that these  $\text{H}_2\text{O}$  lines mainly trace gas that has been heated and compressed by shocks, rather than entrained ambient gas. This latter possibility was suggested by Franklin et al. (2008) on the basis of SWAS observations, but assuming the same physical parameters for the 557 GHz line as for the  $\text{CO}(1-0)$  line. In addition, our maps provided evidence that the excitation conditions and abundance of water in L1448 are fairly constant at the sampled spatial scales. This implies very similar shock properties, which seem to be unaffected by evolutionary effects on the timescales of the outflow propagation. The only exception is the region immediately adjacent to the protostar L1448-C: here an  $\text{H}_2\text{O}$  column density an order of magnitude higher is found relative to the other outflow positions. Part of this on-source emission is associated with the

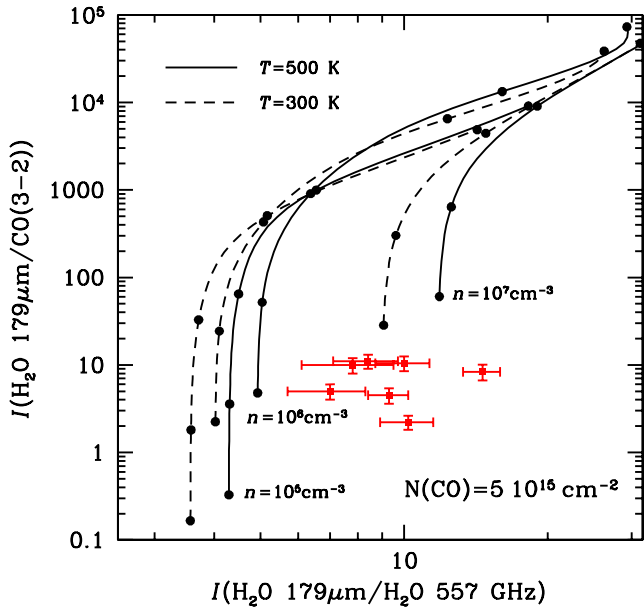
EHV jet where  $\text{H}_2\text{O}$  and  $\text{SiO}$  molecules might be directly synthesized in the atomic free protostellar wind (see also Kristensen et al. 2011).

The temperature of few hundred K inferred along the outflow is much lower than the maximum temperature of shocked molecular gas, as traced by  $\text{H}_2$  near-IR rovibrational lines ( $\sim 2000 \text{ K}$ ), for example. Far-IR  $\text{H}_2\text{O}$  lines at higher excitation observed by ISO in L1448 indicate the presence of hotter gas with  $T \gtrsim 1000 \text{ K}$  (Nisini et al. 1999, 2000), thus suggesting a distribution of gas temperatures similar to what has been inferred for the  $\text{H}_2$  gas. PACS observations of several young sources suggest that the presence of gas components at different temperatures is indeed very common (e.g. Herczeg et al. 2011; Karska et al. 2012; Goicoechea et al. 2012) and that the  $\text{H}_2\text{O}$  abundance is typically higher in the hotter gas (Giannini et al. 2001; Santangelo et al. in prep.).

Considering excitation in a single shock, one can expect that different excitation components are associated with different layers in the post-shock region, and that the low-lying  $\text{H}_2\text{O}$  transitions considered here should trace post-shocked gas layers where



**Fig. 8.**  $\text{H}_2\text{O}$  179  $\mu\text{m}$ /557 GHz ratio vs. the  $\text{H}_2\text{O}$  179  $\mu\text{m}$  intensity (expressed in  $\text{erg s}^{-1} \text{cm}^{-2} \text{sr}^{-1}$ ). Theoretical LVG predictions are plotted for volume densities of  $10^5$ ,  $10^6$  and  $10^7 \text{ cm}^{-3}$ , and for kinetic temperatures of 300 K (dashed line) and 500 K (full line). Along each curve the  $N(\text{o-H}_2\text{O})$  column density varies from  $10^{12}$  to  $10^{16} \text{ cm}^{-2}$  in steps of a factor 10. Open cyan circles refer to intensities measured in a beam of  $38''$ , equal to the beam size of the 557 GHz observations. Filled red circles plot the *unconvolved* PACS intensities. The data point for L1448-C is labeled.



**Fig. 9.** Diagnostic diagram employing the  $\text{H}_2\text{O}$  179  $\mu\text{m}$ /557 GHz vs. the  $\text{H}_2\text{O}$  179  $\mu\text{m}$ /CO(3–2) intensity ratios. Theoretical LVG predictions are plotted for the same parameters as in Fig. 8. The plot assumes a fixed  $N(\text{CO})$  column density of  $5 \times 10^{15} \text{ cm}^{-2}$  (see text for details). Data points refer to intensities measured in a beam of  $38''$ , equal to the beam of the 557 GHz observations.

the gas has already cooled down to a few hundred K. Santangelo et al. (2012) inferred that the ratios of low excitation  $\text{H}_2\text{O}$  lines in the L1448-B2 and R4 spots are consistent with nondissociative J-type shocks, a conclusion also supported by the high inferred densities, which imply a large shock compression factor. In these shocks, as also in C-shocks, high  $\text{H}_2\text{O}$  abundances are

produced in the hot gas through the rapid conversion of atomic oxygen into water when  $T_{\text{kin}}$  exceeds  $\sim 300\text{--}400 \text{ K}$  (Kaufman & Neufeld 2006; Flower & Pineau Des Forêts 2010), and should be maintained long after the gas has cooled down. Hence, we should measure the same high  $\text{H}_2\text{O}$  abundance in both the warm and the hot gas, unless the density is so high to allow a very quick freezeout of gas-phase water onto grain mantles.

For  $n(\text{H}_2) \sim 10^6 \text{ cm}^{-3}$ , Bergin et al. (1996) derived a timescale  $\sim 10^4 \text{ yr}$  for this process. Typical timescales for J-shock propagation at a pre-shock density of  $10^4 \text{ cm}^{-3}$  are shorter than  $10^2 \text{ yr}$  and the timescales are not longer than  $\sim 10^3 \text{ yr}$  even for C-type shocks; hence grain freeze-out will be of minor importance in reducing the gas-phase water column density in the still warm regions of the post-shocked gas. A water abundance lower than that expected to result from endothermic gas-phase reactions could result if most of the oxygen not in CO is frozen out in ice mantles in the pre-shock gas. This possibility is strongly suggested by the very low abundance of  $\text{O}_2$  gas as measured by SWAS and *Odin* in dense molecular clouds, which indicates that atomic oxygen could be largely depleted (Goldsmith et al. 2000; Larsson et al. 2007). However, ice mantles are quickly destroyed by sputtering for shock speeds exceeding  $\sim 10\text{--}15 \text{ km s}^{-1}$ , so freeze-out within the pre-shock gas can be of relevance only for very slow shocks.

A different way to decrease the  $\text{H}_2\text{O}$  abundance in the post-shocked gas could be through photodissociation by a pre-existing far-ultraviolet (FUV) field. Shock regions located along the outflow cavity wall close to the protostar could be directly exposed to the central source FUV field (e.g. Visser et al. 2012). Far from the source, the only way to produce a significant FUV field is through fast J-type dissociative shocks. This scenario assumes a superposition of two shocks at different velocities: this is expected, e.g., in jet-driven outflows where a fast dissociative shock (i.e. the jet shock or Mach disk) decelerates the jet and a low-speed shock accelerates the ambient medium (e.g. Raga & Cabrit 1993). The effect of FUV photons, generated by a J-shock, impinging on the region behind a nondissociative shock has been discussed in Snell et al. (2005). Their result is that these photons are not effective in decreasing the abundance of the hot  $\text{H}_2\text{O}$  produced at the shock front, since here the timescales for  $\text{H}_2\text{O}$  formation are extremely short. However, in the post-shocked cooling region, water can be rapidly dissociated and consequently the  $\text{H}_2\text{O}$  abundance decreases significantly from the peak value at the shock front. Timescales for  $\text{H}_2\text{O}$  dissociation depend on the strength of the FUV field and the degree of FUV shielding (Lockett et al. 1999). Direct exposure to a radiation field with  $G_0 > \text{few} \times 10$  (where  $G_0$  is the intensity of the radiation field relative to its average interstellar value) returns all oxygen to atomic form very quickly. If the field is shielded by an  $A_v \sim 1 \text{ mag}$ , timescales for converting  $\text{H}_2\text{O}$  back to oxygen are of about thousands of years and still compatible with the outflow dynamical timescale. Snell et al. determined that the column of post-shocked  $\text{H}_2\text{O}$  behind a C-type shock should scale with the FUV field as  $\sim 4 \times 10^{15} (n_0/10^4 \text{ cm}^{-3})(v_s/10 \text{ km s}^{-1})G_0^{-1}$ , for a shock of velocity  $v_s$  in gas of pre-shock density  $10^4 \text{ cm}^{-3}$ . Our derived column densities of about  $10^{14} \text{ cm}^{-2}$  therefore imply the presence of a FUV field  $G_0 \sim 25(n_0/10^4 \text{ cm}^{-3})^{-1}(v_s/10 \text{ km s}^{-1})^{-1} \text{ cm}^{-2}$  for such a shock. Additional modeling will be required to determine the exact properties of a J-shock capable of producing the necessary FUV field. However, the jet speed (with a projected velocity up to  $80 \text{ km s}^{-1}$  along the line of sight) is certainly high enough to drive a J-type shock that emits strongly at FUV wavelengths. A dissociative shock that gives rise to

ionizing photons is suggested, in at least specific positions, by the detection of [Fe II] emission along the L1448 outflow by Neufeld et al. (2009) and of OH emission toward the B2 clump (Santangelo et al. in prep.). Shocks close to the sources could instead be directly exposed to the source FUV field expanding in the envelope cavity, whose presence is revealed by the scattered light emission detected in the *Spitzer* IRAC images (Tobin et al. 2007). A different scenario can be also considered, where the hot and warm H<sub>2</sub>O components are produced in two separate nondissociative shocks with different velocities. Slow C-type shocks with velocities  $\lesssim 15 \text{ km s}^{-1}$  produce post-shocked temperatures that never exceed  $\sim 300\text{--}400 \text{ K}$  (e.g. Kaufman & Neufeld 1996): at these temperatures, the conversion of oxygen into water proceeds at very low efficiency and therefore the H<sub>2</sub>O abundance does not dramatically increase relative to its to pre-shock value on the timescale of shock evolution. In addition, as discussed before, at these low velocities ice mantles are not efficiently sputtered; therefore the release of water from grains is also inhibited. This scenario would imply, however, that the bulk of the 557 GHz line that we observe originates in a shock with a speed much lower than the actual velocity as measured from the line profile.

## 6. Conclusions

H<sub>2</sub>O 2<sub>12</sub>–1<sub>01</sub> and 1<sub>10</sub>–1<sub>01</sub> maps of the L1448 outflow were analyzed and compared with CO(3–2), SiO(8–7) and H<sub>2</sub> mid-IR lines to infer the origin and properties of H<sub>2</sub>O emission in this prototypical class 0 outflow. The main results of our analysis can be summarized as follows:

- On the 12'' spatial scale provided by PACS, the 179  $\mu\text{m}$  line distribution appears to be patchy, with emission peaks localized in shock spots along the outflow. Strong emission is observed toward the L1448-C source, which drives the main outflow in the region, whose spatial extent covers the colimated and compact molecular jet observed in the H<sub>2</sub> S(0) and S(1) lines.
- The kinematical information provided by the 557 GHz HIFI observations reveals that water lines trace the same velocity range as the CO gas, but present a remarkably different profile, which is dominated by emission at intermediate velocities (i.e.  $\pm 10\text{--}30 \text{ km s}^{-1}$ ). Emission from gas at extreme velocities (i.e. up to  $80 \text{ km s}^{-1}$ ) is detected but it is not as prominent as in CO. We analyzed the velocity dependence of the H<sub>2</sub>O/CO(3–2) ratio, finding that this ratio varies significantly with velocity. An initial H<sub>2</sub>O/CO(3–2) increase is followed by a drop at velocity  $\sim 30 \text{ km s}^{-1}$ . These velocity variations are indicative of strong changes in the physical and chemical conditions with the flow speed and cannot be explained by H<sub>2</sub>O abundance variations alone.
- When compared with SiO(8–7) emission, detected in our map only close to the L1448-C source, H<sub>2</sub>O emission presents significant kinematical differences. SiO is associated only with the EHV gas and is not detected from the broad H<sub>2</sub>O emission component at intermediate velocity. The low H<sub>2</sub>O/SiO ratio inferred in the EHV bullets is not reproduced by shock models and points to an origin from dust-free gas directly ejected from the protostellar wind. The absence of SiO in the broad H<sub>2</sub>O component remains puzzling, however, and could be explained by assuming that grain disruption is inhibited in the very dense H<sub>2</sub>O emitting region.
- From the H<sub>2</sub>O observed line ratio and absolute intensities and from the additional constraints derived from

H<sub>2</sub> lines observed with *Spitzer*, we infer that the gas responsible for the bulk of the water emission is warm, with  $T_{\text{kin}} \sim 300\text{--}500 \text{ K}$ , and very dense, with  $n_{\text{H}_2} \sim 5 \times 10^6 \text{ cm}^{-3}$ . These parameters, as well as the association of the 179  $\mu\text{m}$  emission with specific shock spots, indicate that these H<sub>2</sub>O lines mainly trace gas that has been heated and compressed by shocks and not entrained ambient gas, which instead mainly contributes to the CO(3–2) emission.

- The H<sub>2</sub>O abundance of the gas component traced by the 2<sub>12</sub>–1<sub>01</sub> and 1<sub>10</sub>–1<sub>01</sub> lines was directly measured comparing the H<sub>2</sub>O column density with the H<sub>2</sub> column density inferred from the H<sub>2</sub> S(1) 17  $\mu\text{m}$  line: values of about  $0.5\text{--}1 \times 10^{-6}$  are found, with small variations along the outflow, but these increase by roughly an order of magnitude toward the L1448-C source. This low abundance value, associated with warm gas at a few hundred K, suggests that a diffuse FUV field may act to dissociate the freshly formed water in the post-shock cooling regions. Alternative possibilities, such as H<sub>2</sub>O formation in very low-velocity C-type shocks, or freeze-out of H<sub>2</sub>O molecules on dust grains in the post-shocked gas, seem to provide a less compelling explanation of our findings.

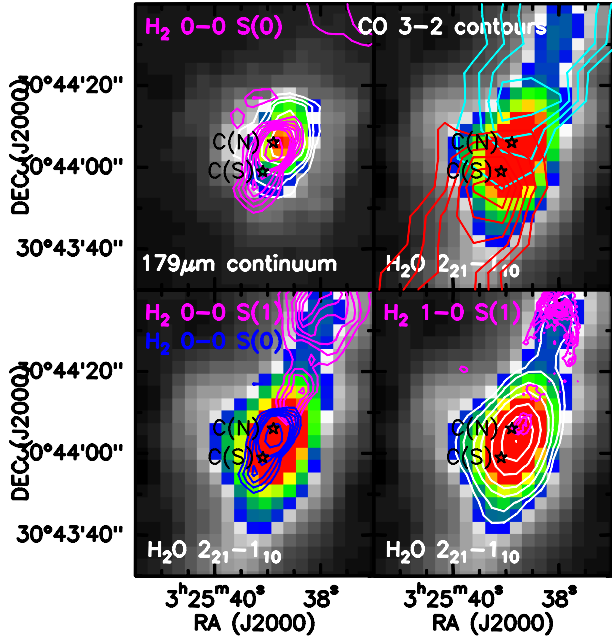
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**Fig. A.1.** Maps of the 179  $\mu\text{m}$  line and continuum emission in the region around L1448-C sources, compared with CO(3–2) and H<sub>2</sub> lines at different excitation, namely the 0–0 S(0)(28  $\mu\text{m}$ ), 0–0 S(1)(17  $\mu\text{m}$ ), and 1–0 S(1)(2.12  $\mu\text{m}$ ). White contours, shown in the *bottom right* and *upper left* panels, for the line and continuum emission respectively, are drawn at the following values:  $1.5, 2.0, 3.0, 4.0, 6.0, 8.0 \times 10^{-5} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$  for the line emission, and  $0.6, 0.8, 1.2, 1.6 \times 10^{-3} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$  for the continuum emission.

## Appendix A: Comparison of different tracers around the L1448-C and N regions

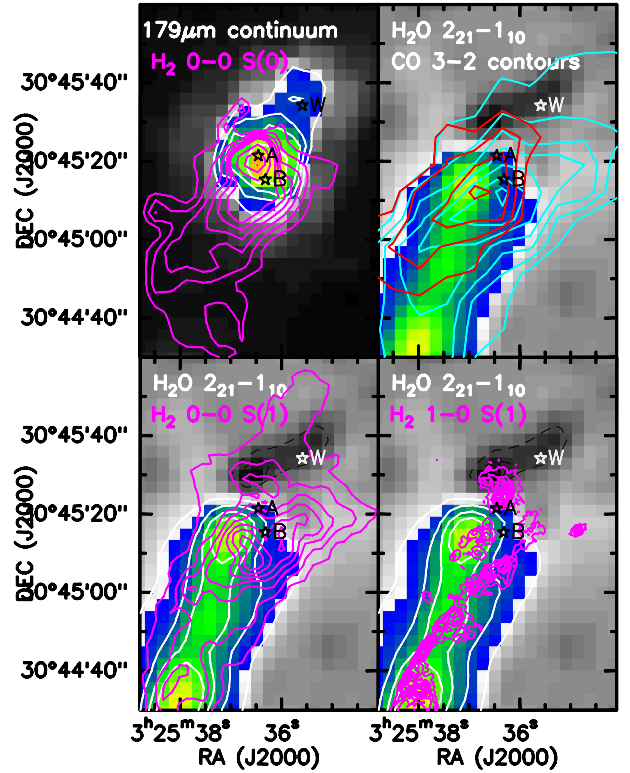
### A.1. L1448-C

Figure A.1 shows an enlargement of the 179  $\mu\text{m}$  emission in the region around L1448-C. Both the continuum and the H<sub>2</sub>O emission are displayed, with superimposed contours of the CO(3–2) and different H<sub>2</sub> lines (near-IR, from Davis & Smith 1996, and *Spitzer* from Giannini et al. 2011). The 179  $\mu\text{m}$  line peaks toward the C(N) source but is elongated along the direction of the molecular jet, as discussed in Sect. 4.1, which in the figure is traced by the H<sub>2</sub> 0–0 S(0) and S(1) lines and comprises the inner peaks in the CO(3–2) emission. The H<sub>2</sub> S(0) line is observed on source and along the SE (redshifted) jet, while the S(1) line is detected only toward the NW blueshifted jet and toward the B1 region. Extinction is the likely reason why the S(1) line is not detected on-source. Assuming a temperature of about 300 K, the ratio between the S(0) flux and the S(1) upper limit implies a lower limit of  $A_V \sim 65$  mag toward the source and 45 mag in the redshifted jet.

Finally, Fig. A.1 shows the overlay with the H<sub>2</sub> 2.12  $\mu\text{m}$  line. At the central source position the line is almost totally extinguished and thus no NIR emission is associated with the jet. The 2.12  $\mu\text{m}$  line emission traces instead a bow shock in the blue lobe originated in the interaction of the jet with the ambient medium, which also shows up also as a clump of H<sub>2</sub>O emission.

### A.2. L1448-N

The 179  $\mu\text{m}$  continuum image, displayed in Fig. A.2, shows unresolved emission from the three sources of the L1448-N cluster, whose peak coincides with the N(A) source. The H<sub>2</sub> S(0)

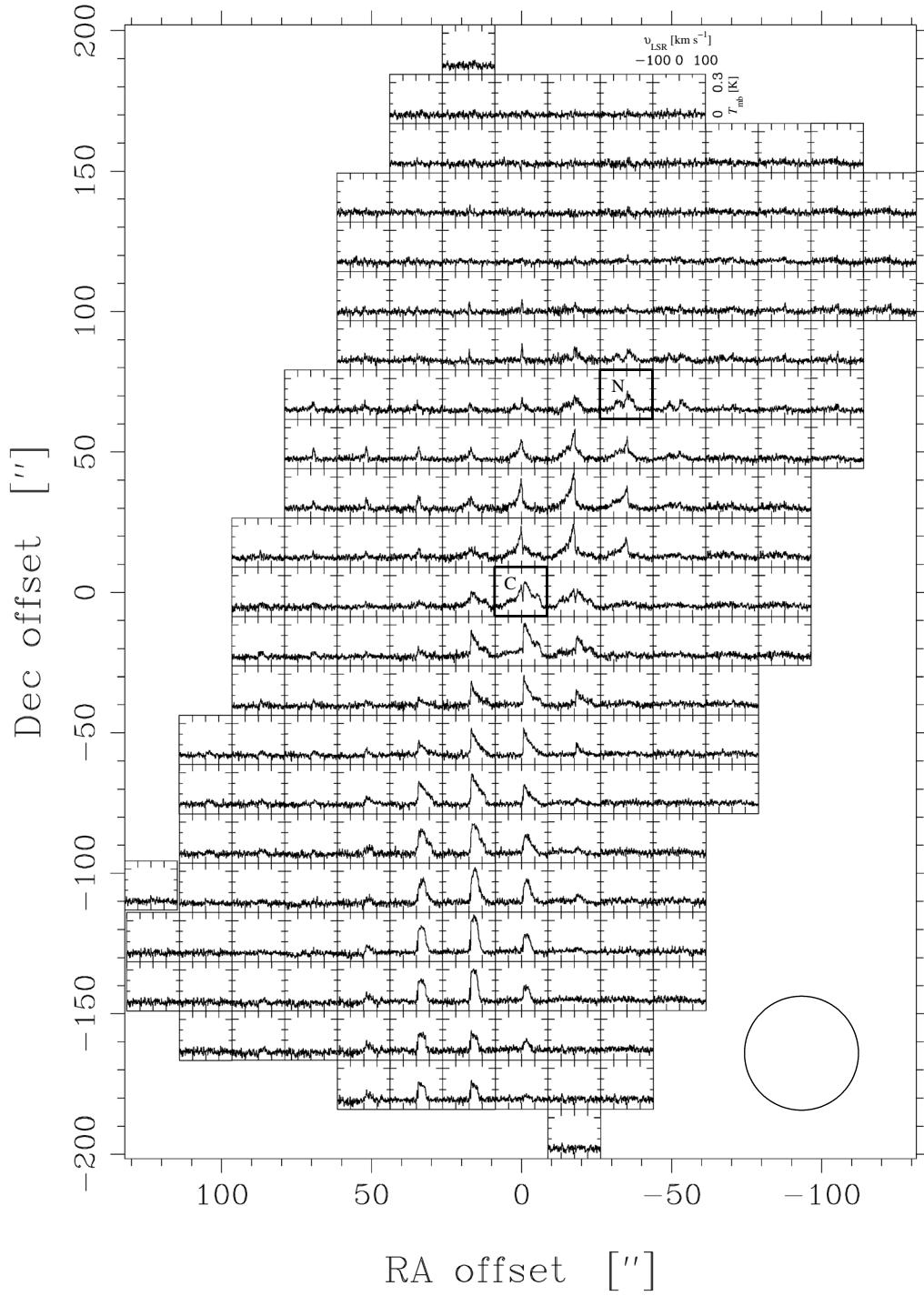


**Fig. A.2.** Same as Fig. A.1 for a region around L1448-N. In this case, white contours are drawn for the line and continuum emission with the following values:  $0.6, 1.2, 1.8, 2.4, 4.0 \times 10^{-5} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$  (line) and  $0.6, 0.8, 1.2, 1.6 \times 10^{-3} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$  (continuum). A contour of black broken line delineates the absorption region.

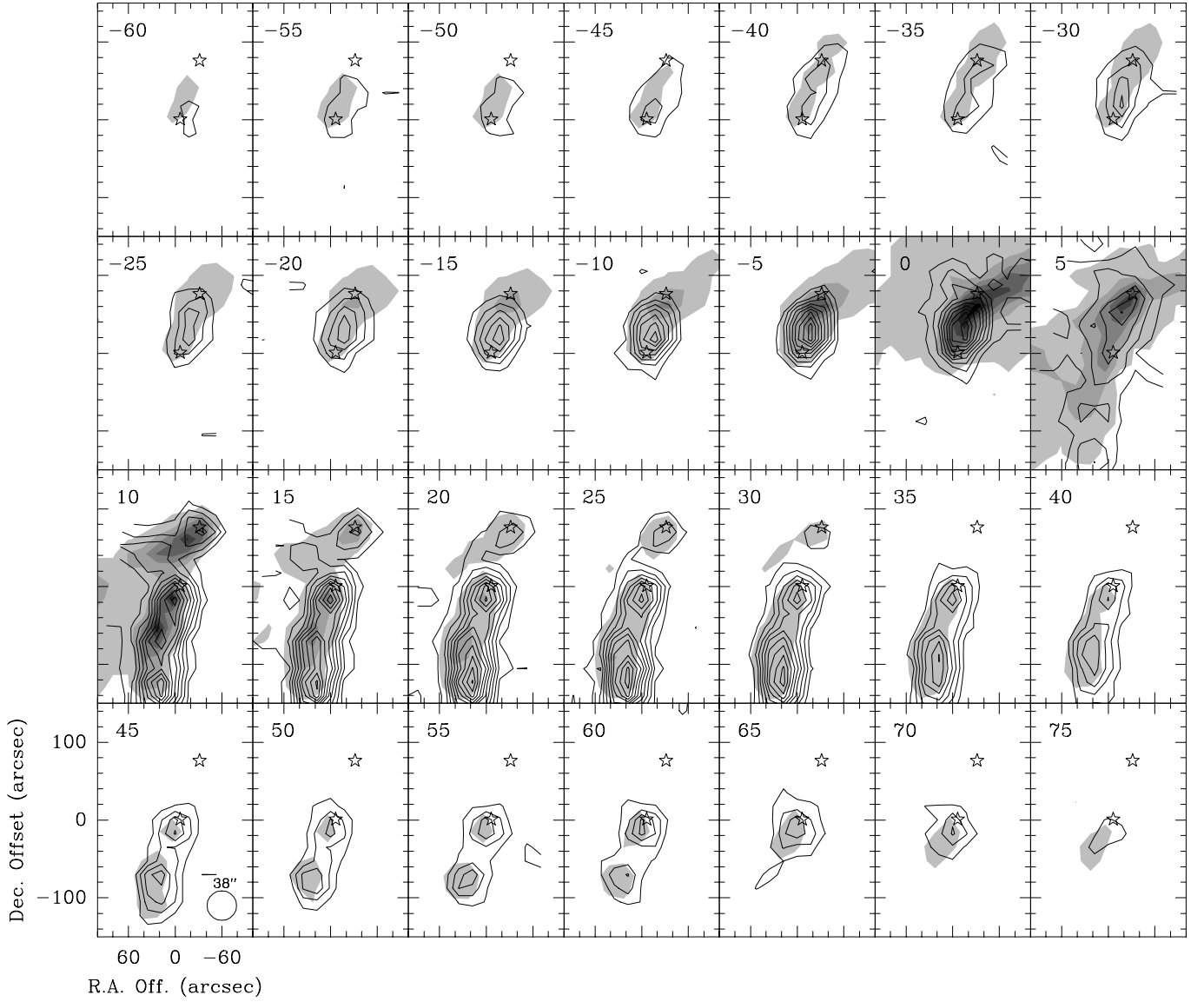
emission, overlaid on the continuum image, also peaks toward N(A), indicating large columns of cold gas. As described in Sect. 3.1, only two of the three sources power outflows, resolved through interferometric observations by Girart et al. (2001) and Kwon et al. (2006). The outflow from N(A) is very compact and is seen almost perpendicular to the line of sight. By contrast, the outflow from N(B) is more elongated and extends to about 100'' from the driving source (at PA = 110°) both in the blue- and redshifted lobes. In our CO map we cannot distinguish the blueshifted gas of these two outflows from the large-scale L1448-C main outflow; however, we identify redshifted emission at velocity between  $\sim +1$  and  $+20 \text{ km s}^{-1}$  mainly originating from the N(B) flow (see also Fig. 3, left).

In contrast with L1448-C, the 179  $\mu\text{m}$  line emission does not peak toward the sources of this region, but is associated only with the outflow: bright emission is, in particular, observed close to the H<sub>2</sub> S(1) and to the CO(3–2) redshifted peaks. The bulk of the water emission, however, does not follow the curving H<sub>2</sub> large-scale jet driven by L1448-C, but seems to be associated with the 2.12  $\mu\text{m}$  H<sub>2</sub> emission (knots Y/Z in Davis & Smith 1996), excited in the L1448-N(A/B) outflows. This could be a density effect, if one assumes that the density at the base of the N(A/B) flows is higher than the gas along the large-scale jet.

North of the N(A/B) sources the water emission decreases abruptly, while an absorption line of water appears, that follows the 179  $\mu\text{m}$  continuum. The water absorption region lies along the line of sight of the L1448-N reflection nebula, visible in the IR images at both 2.12  $\mu\text{m}$  and in the *Spitzer* IRAC maps (Davis & Smith 1996; Tobin et al. 2007). This evidence suggests that the cold water in the blueshifted outflow is seen in absorption against the nebula, which therefore lies in the background.

Appendix B: H<sub>2</sub>O 557 GHz spectra and velocity channel maps

**Fig. B.1.** HIFI map of the H<sub>2</sub>O 1<sub>10</sub>–1<sub>01</sub> 557 GHz line. The data have been regridded onto a regular grid of 18'' of spacing (i.e. half of the instrumental HPBW, which is displayed in the figure as reference) and binned at 1 km s<sup>-1</sup> resolution. The map is centered on the L1448-C source at  $\alpha_{2000} = 03^{\text{h}}25^{\text{m}}38.4^{\text{s}}$ ,  $\delta_{J2000} = +30^{\circ}44'06''$ .



**Fig. B.2.** Contours of integrated  $\text{H}_2\text{O}$  557 GHz intensities in velocity intervals of  $\Delta V = 5 \text{ km s}^{-1}$  superimposed on gray-scale maps of the  $\text{CO}(3-2)$  intensity integrated in the same bins. The center velocity of the bins is indicated in each panel.  $\text{H}_2\text{O}$  contours are in steps of  $0.03 \text{ K km s}^{-1}$  and the first contour is at  $0.03 \text{ K km s}^{-1}$  (equivalent to  $3\sigma$ ), while CO gray levels are in steps of  $1.2 \text{ K km s}^{-1}$  and the first contour is at  $0.2 \text{ K km s}^{-1}$ . The starred symbols represent the positions of the L1448-C and L1448-N sources.